Appendix D

Environmental Conditions & Operations: Contemporary Russian Experience

D.0 ENVIRONMENTAL CONDITIONS & OPERATIONS: CONTEMPORARY RUSSIAN EXPERIENCE

This appendix presents additional findings obtained during an information gathering trip to Moscow and St. Petersburg in April 2007. This appendix presents both general and specific information on Russian Arctic sea ice and iceberg research, methodologies, and recent findings. In particular, discussion on research carried out in the Shtokman field area is presented. Information with respect to Gulf of Finland ice conditions is also discussed.

D.1 General

The large-scale evaluation and monitoring of environmental conditions in the Russian sector of the Arctic was for many years a high priority task. The huge extent of the Arctic coastal zone stretching from Scandinavia to Alaska, and the humane, transportation, industrial and military needs associated with these vast areas required substantial efforts supported by the Russian Government. The discovery of large oil and gas resources on the Russian Arctic shelf and in the areas of both eastern and western Siberia, located on land in the adjacent coastal zone, has generated a substantial increase in these activities in recent years. The goals and the technology of the environmental monitoring and research surveys also changed to reflect the requirements of oil and gas exploration.

The Arctic and Antarctic Research Institute (AARI) in St. Petersburg has been at the forefront of this work in Russia for many years. Environmental surveys conducted by AARI have been used for practically all oil and gas exploration projects in Russia. The institute also took an active role in large projects executed during previous years in the Arctic and Sub-Arctic areas of Russia by foreign companies (Sakhalin Island Development is one major example). During an information collection trip to Russia conducted in April 2007 for the current study, a series of publications on work recently performed by the AARI was acquired in the Russian National Library in St. Petersburg. Publications included works by Ryabchenko et al. (2003); Zubakin et al. (2004a); Borodulin et al. (2004); Mironov et al. (2001); Zubakin et al. (2004b); Naumov (2004); Buzin (2004a); Buzin (2004b); Zubakin et al. (2004c); and Drabkin and Lebedev (2001). The subsequent sections of this appendix present a technical review of these publications.

The original publications are all in Russian and thus required translation. Best efforts were made to maintain the technical content of the publications and to present the most important results of the surveys and investigations performed by the Russian researchers.

D.2 Methodology of Collection and Analysis of Arctic Shelf Environmental Data

Several recent AARI publications (Zubakin et al., 2004a; Borodulin et al., 2004) clearly indicate that the methodology of environmental data collection is geared towards the subsequent application of this data for practical engineering tasks, such as the evaluation of ice loads on structures, planning of marine operations, ice management, etc. The typical organization of data collection begins from the aerial choice of the appropriate ice floe (Figure D-1, Zubakin et al., 2004a). The expedition research vessel is fixed by ice anchors to the large ice floe, the vessel-based helicopter conducts aerial photography of the region, and the research party is launched on the ice floe surface. The following range of parameters and observations listed in Zubakin et al. (2004a) gives some idea on the scale and scope of investigation normally performed at the site (ice station):

a) Topographic Survey of Ice Cover

This survey includes the determination of ridge heights at points identified in the relative (local) coordinate system, three-dimensional models of ice cover, snow layer thickness, complete geometry of ridge formations, and dimensions of individual ice blocks.

b) Sonar Sounding of Underwater Part of Ice Cover

Visual interpretation of the lower part of ice cover, digitalization of images and evaluation of the ridge keel dimensions.

c) Investigation of Ice Parameters by Through-Drilling

Ice thickness, void distribution, coring of samples for evaluation of physical and mechanical properties, evaluation of the thickness of the consolidated layer, and calculation of ridge density coefficients.

d) Investigation of Physical and Mechanical Properties of Ice (Core Testing)

Distribution of temperature, salinity and density over the ice thickness, ice strength parameters, texture and structural ice features.

e) Hydrology Observations

Current parameters, temperature and salinity of sea water

f) Investigations of Ice Drift

Parameters of short-period ice drift recorded through vessel drift observations (ice station coordinates monitoring)

g) Underwater Activities

Technical photography and video of the ice cover lower surface.

h) Meteorology Observations

Hourly wind velocity and direction observations. Measurements of air temperature and atmospheric pressure.

i) Helicopter Ice Cover Survey

Characterization of the uneven top surface of ice cover and number of ridge ranges. Collection of ice samples for evaluation of physical and mechanical properties. Detailed mapping of ice conditions in the general area of the expedition work. Evaluation of the ridge height over significant observation areas (polygons) using the aerial photography technique.

j) Iceberg Survey

Overall number of icebergs, their dimensions and strength parameters, vertical structure of current fields, and associated vortices around the icebergs.

k) Satellite Monitoring of Condition of Ice Cover Using Vessel-based Equipment

Distribution of ice cover in the general area of the expedition survey.

According to Zubakin et al. (2004a), one of the relatively new areas of the AARI investigations associated with evaluation of environmental conditions is the large-scale strength test of ice and compression testing by interaction with an indenter. The lateral compression loading in these tests is applied to an ice cantilever having a thickness of 46-48 cm.

A review of AARI publications indicates that they place a significant focus on statistical reduction of test and observation data. This work is conducted taking into consideration the three-dimensional variability of ice properties. The important area of data handling is evaluation of ice strength parameters that have a low probability of occurrence. This approach is considered as particularly important by AARI, because research clients are usually interested in the maximum (lower probability) values of the ice strength. These values are normally used as the design criteria for engineering structures. Reliable criteria for ice/structure interaction analysis are produced when core testing data is combined with the results of the large-scale strength tests, and with the output of the corresponding finite element model calculations.

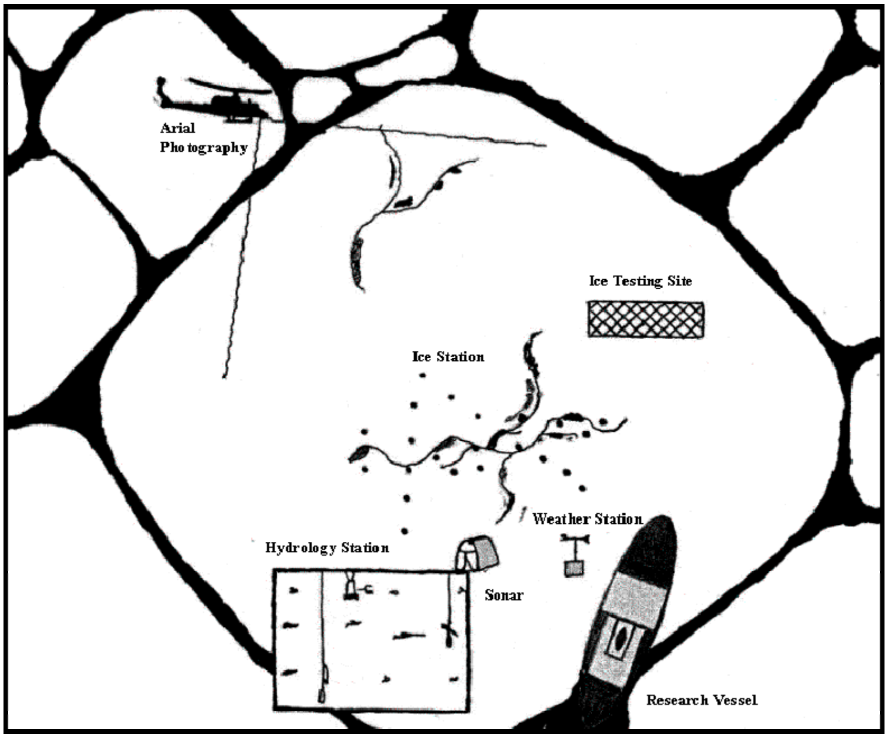

Figure D-1: Layout of Typical Ice Survey (Zubakin et al., 2004a)

D.3 Evaluation of Ice Conditions in the Southeast Barents Sea and Southwest Kara Sea – General

The systematic observations of ice conditions in these areas of the Russian Arctic began in 1930's, however their goal at that time was primarily to provide the necessary information for transportation along the Northern Sea Route from the Barents Sea to the Sea of Japan. The contemporary surge in these activities began in the 90's when oil and gas exploration on the Arctic shelf was identified as no less (if not more) important of a task. This new task also required an implementation of substantial changes in environmental survey work scopes and procedures.

D.3.1 Southeast Barents

Ice data observations for this area are available from 1916; however, the most detailed evaluations were initiated in the late 90's for the "Prirazlomnaya" platform. The Pechora Sea, which is usually considered in the Southeast Barents zone, is characterized primarily by consolidated first-year ice conditions, as well as possibly by the presence of thicker ice carried out of the Kara Sea. Relatively thin ice from the White Sea is also observed in the area. During the 20th century, maximum ice coverage of 71 percent in the area was observed in December 1997. The calculated 50-year ice cover is 68 percent, and 100–year event is 75 percent.

D.3.2 Southwest Kara

The Kara Sea is covered with ice during three-quarters of the year; however, it becomes almost totally free of ice during several summer months. Ice conditions in the sea, in addition to the seasonal changes, have substantial year-to-year variability. For instance, yearly variations in summer ice coverage can fluctuate by +/- 45 percent. The AARI observed that these yearly variations occur in rather similar fashion in different regions of the sea.

The total amount of available data on ice conditions in the Southwest Kara may be illustrated by the following information, quoted in Mironov et al. (2001):

- Between 1986 and 2001 the AARI had generated 500 weekly ice maps of the area from satellite-based photography

- Hydro-meteorological observations are conducted at 11 seashore or island stations. Standard sets of these observations include the dates of basic sea ice spring and autumn phase transformations, as well as land-fast ice thickness measurements.

Foreign specialized organizations have shown interest in environmental condition surveys of the Kara Sea. For instance, a fairly detailed plan for the investigation of ice conditions in the Pechora Sea and Kara Sea coastal regions was developed in 2001-2002 by Russian specialists in collaboration with Nansen Environmental and Remote Sensing Center in Bergen (Sandven et al., n.d.). The plan indicates the possibility of a successful application of SAR imaging for the evaluation of fast ice formation and deterioration, as well as for the dynamics of the shore and flaw recurring polynyas.

D.4 Evaluation of Environmental Conditions at Shtokman Field

D.4.1 General Description of Conditions in the Area

During recent years, a concerted effort has been dedicated to surveying conditions in the Shtokman field within the Barents Sea (Zubakin et al., 2004b; Naumov, 2004; Buzin, 2004a; Buzin, 2004b; Zubakin et al., 2004c). This interest is understandable since Shtokman gas reserves are estimated at 3.3 trillion cubic meters and yearly production is assumed to reach 60 billion cubic meters. Large projects for the production and delivery of liquefied gas from Shtokman to Europe and the US are being developed (Buzin, 2004b).

The location of Shtokman is illustrated in Figure D-2 (Zubakin et al., 2004b). This figure also shows the approximate limits of three major subdivisions of the Barents Sea that are commonly referred to in Russian research / survey work and publications (including the South-East Region described in the previous sub-section).

Unfortunately, the unique prospects for exploration at Shtokman are accompanied by no less unique environmental and operational conditions. In general, these include a water depth of 980 ft (300 m), complicated seabed relief, large 370 mile (600 km) distance offshore, winds up to 54 kts (27 m/s), waves up to 69 ft (21 m), the possibility for icing and the presence of ice (including two-year floes) and icebergs. The combination of environmental and operational conditions existing at Shtokman makes the exploration in this area probably the most difficult on the Arctic shelf (Buzin, 2004b).

It was determined that the highest ice coverage in the area occurs in April. Probabilities of ice coverage limits in April are shown in Figure D-3 (Zubakin et al., 2004b). The key idea of the general approach used to evaluate ice conditions at Shtokman was that a substantially larger area (then the gas field itself) was to be chosen for systematic monitoring surveys. This area is shown by hatching in Figure D-2 and by the dotted line in Figure D-3. Correlation analysis (which is widely used in AARI ice surveys) confirmed the reliability of this approach; as can be seen in Figure D-3, the chosen monitoring area extends between the 10 and 70 percent probability levels for April ice coverage limits in the Barents.

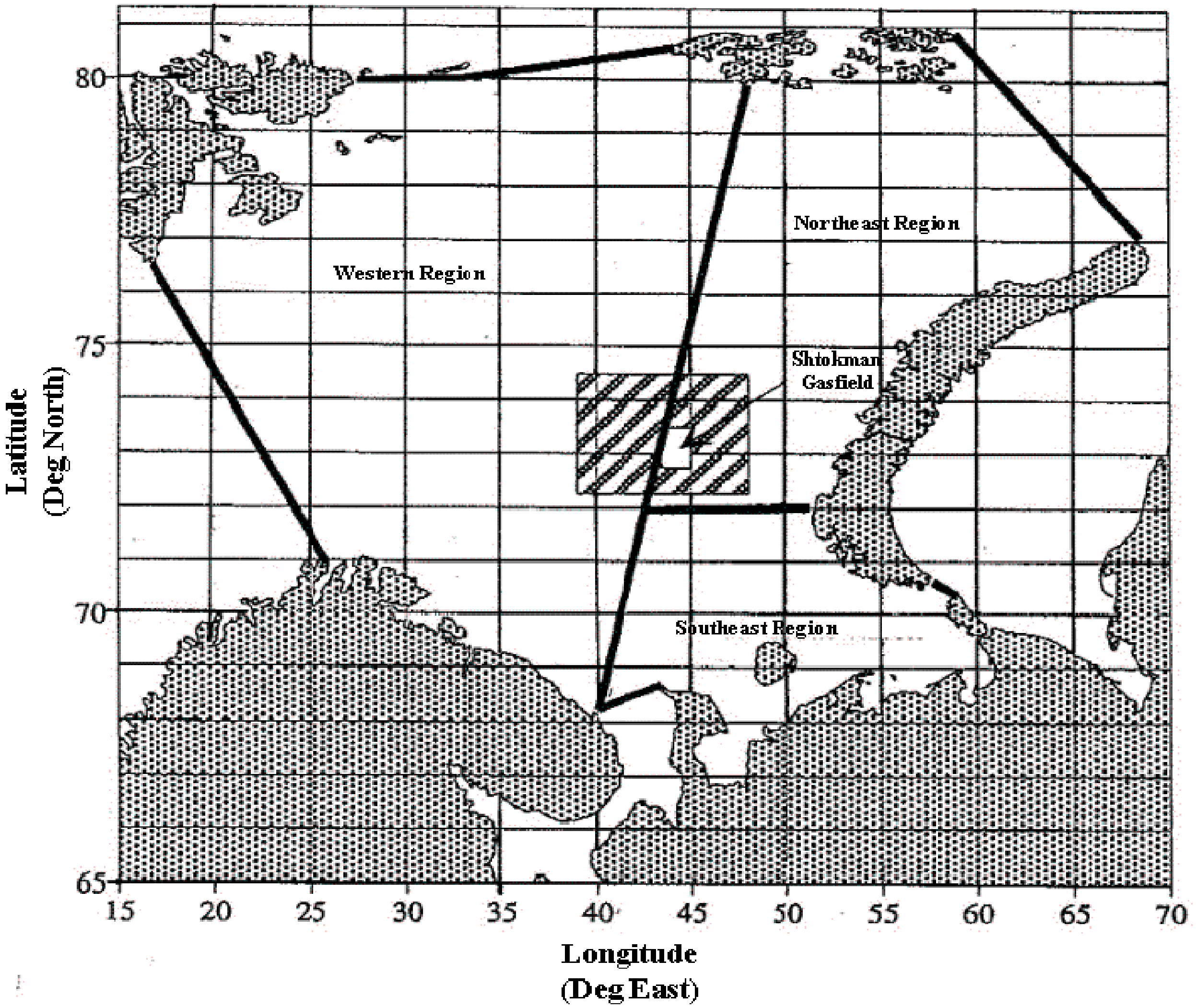

Figure D-2: Barents Sea Regions (Zubakin et al., 2004b)

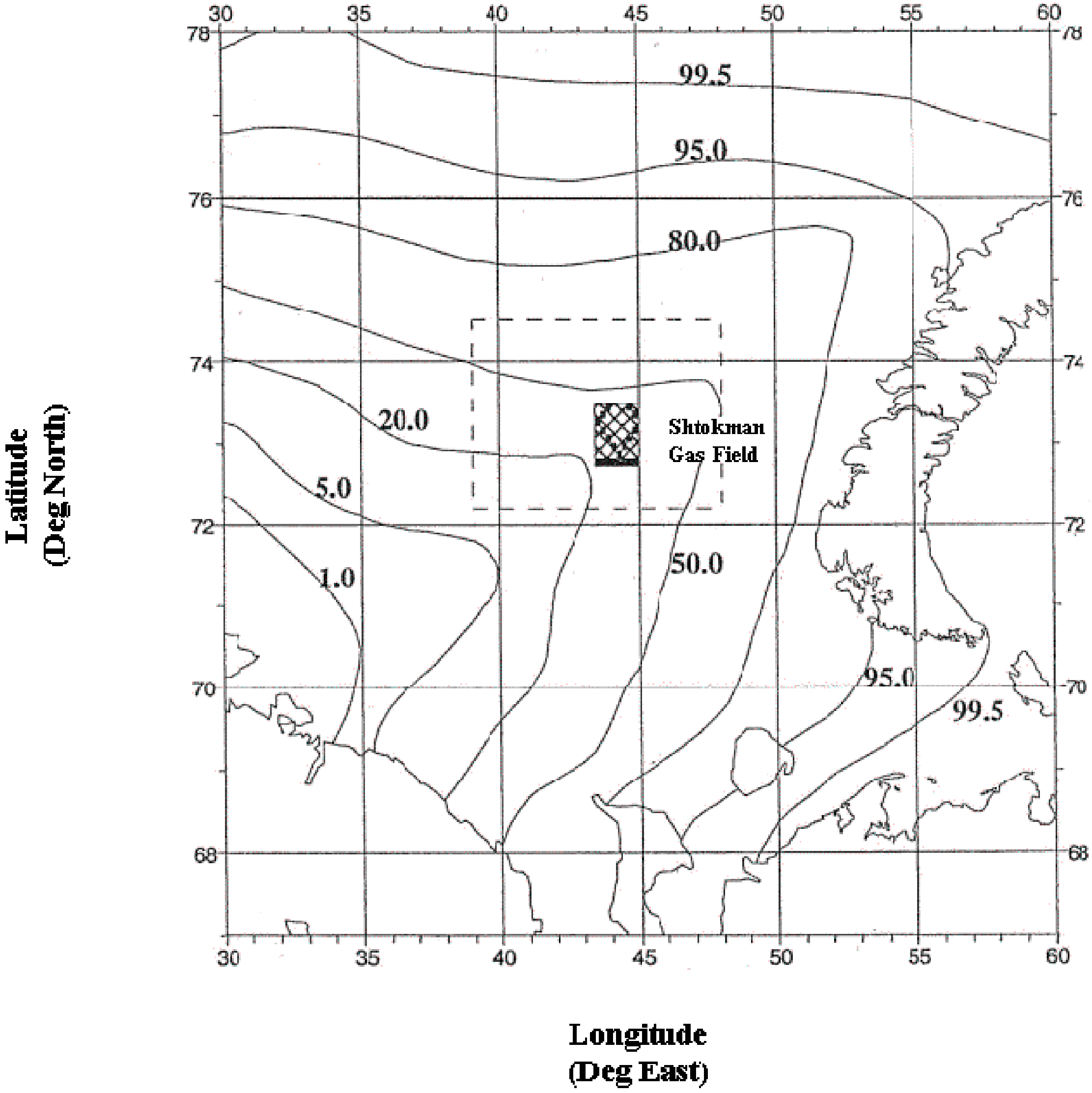

Figure D-3: Probability of Ice Coverage Limits In April in Barents Sea (percent) (Zubakin et al., 2004b)

Sea ice studies carried out for the Shtokman field also examined the distribution of the number of days with ice in the area by months within each year (from 1900 to 2003), dynamics of ice edge penetration into the central and eastern parts of the sea, observations of ice drift from at least five alternative directions (including correlation of this drift with predominant wind directions), and a separate evaluation performed for two-year ice. All types of analysis and multi-parametric inter-dependencies identified in the studies were screened to determine the most reliable means of forecasting ice conditions within the relatively small Shtokman field area.

The following is a sample of conclusions from the AARI Shtokman studies, which may be most interesting for oil and gas exploration and design of engineering structures at the site (Zubakin et al., 2004b):

- Average April ice coverage in the Barents (100 years data base) is 66 percent, but this value has only limited correlation with ice coverage of the area chosen for monitoring conditions at Shtokman.

- The initial period of exploration at Shtokman during 1988-1996 (exploration drilling, evaluation of reserves and creation of Russian and International consortiums), coincided with reduced ice coverage in Barents (25 percent in 1995) and with a period of absence in the Shtokman area.

- The most frequent periods of ice presence in the area occur every two or three years. This phenomenon points to the merits of a “quasi-two-year” cycle theory of hydro-meteorological conditions in the near-Atlantic sector of Arctic.

- Barents Sea ice typically has variable age even in winter, which creates conditions for the formation of ice fields consisting of ice with different properties. North of Shtokman, broken sections of ice fields with 0.3 mile (0.5 km) diameters may be found. There are also larger fields, up to 1.2 miles (2 km), as well as the giant features with diameters up to 6.2 miles (10 km).

- The inclusions of thick 4.9 ft (1.5m) one-year ice may constitute up to 20 percent of the ice cover. During a 2001 expedition, however, ice thicknesses of up to 2m were measured (it should be noted that this information is related to the regions located at 78°N, which is rather far North of Shtokman, see Figure D-3). During the same 2001 expedition, ridge sails of up to 13 ft (4 m) and keels as deep as 44 ft (13.5 m) were recorded.

- During the 2003 winter season, incursions of two-year ice from the North-west Kara were recorded by satellite, ship stations, helicopter and ice-based stations. The measured thickness of this two-year ice ranged from 7.2-8.9 ft (2.2-2.7 m) and its southernmost location was 74°N. This is well inside the monitoring area, but still North of Shtokman (see Figure D-3); however, at the time North-west winds could have driven the heavy ice to Shtokman within 7-10 days. Consequently, the presence of two-year ice features at Shtokman should be considered as a realistic design condition for exploration and development activities.

D.4.2 Distribution of Icebergs & Evaluation of Probability of Collision with Platform

Icebergs are considered one of the most, if not the most serious obstacle for oil and gas exploration at the Shtokman field. Potential sources of icebergs are the glaciers of Arctic archipelagoes, such as Spitsbergen, Franz Joseph Land, Novaya Zemlya as well as Severnaya Zemlya. There is also a possibility for transients from the Canadian Arctic Archipelago. The source nearest to Shtokman is the Northern island of Novaya Zemlya with glaciers having a front length of 117 km.

The Russian database for icebergs in the Barents and Kara seas (1888-1991) includes over 20,000 sightings (the records contain sighting dates, number of icebergs observed, and their coordinates). The number of icebergs in the Barents is illustrated in Figure D-4 (Naumov, 2004). In Figure D-4 the individual square areas are 2° latitude X 5° longitude. The numerator represents the maximum number of iceberg sightings during a single aerial survey, while the denominator indicates the total number of sightings during the survey period.

AARI researchers developed a range of field data reduction procedures allowing the “filtration” of repetitious sightings and evaluation of probability of iceberg appearance within a certain area (Naumov, 2004). For the Shtokman field, the area with coordinates 72-74°N and 40-45°E was chosen. The analysis performed for the whole period of observations yielded the following distribution (probable maximum number of icebergs in the area once in an “N” year period, plus / minus confidence limits range):

- 10 years - 7 (plus / minus 2)
- 50 years - 10 (plus / minus 4)
- 20 years - 8 (plus / minus 3)
- 100 years - 11 (plus / minus 6)

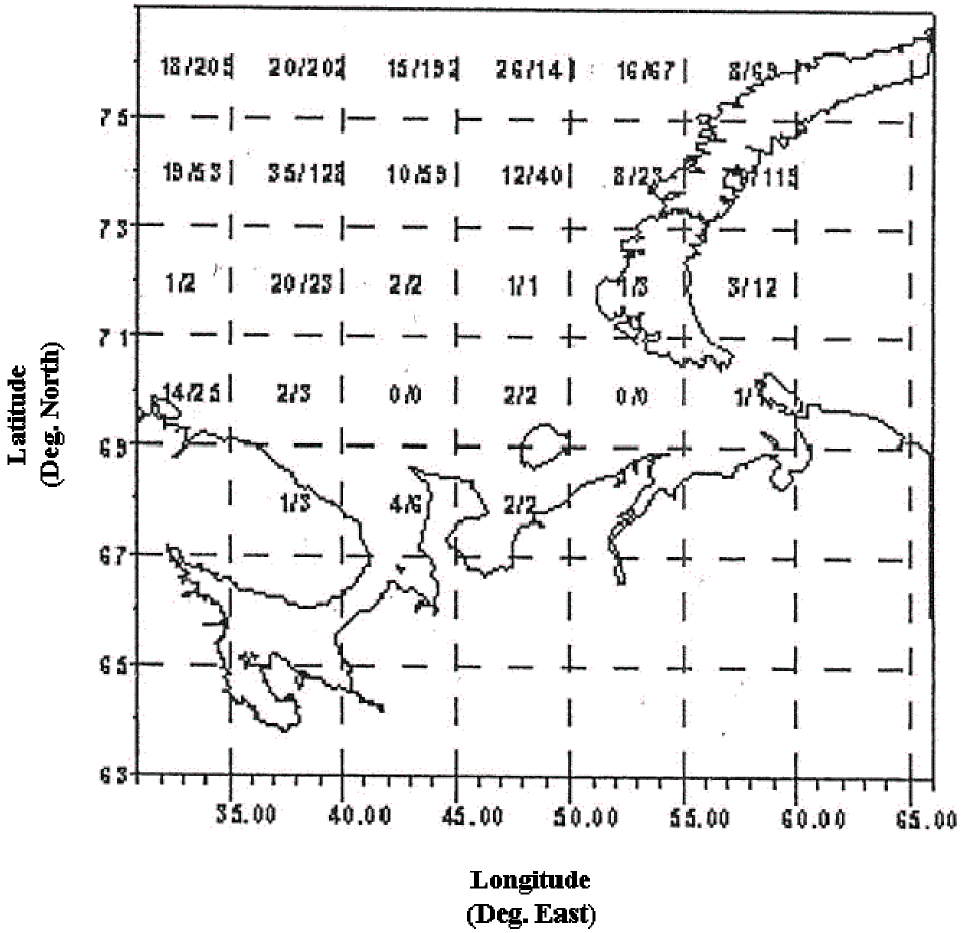

Figure D-4: Distribution of Observed Number of Icebergs in Central and Southern Regions of the Barents Sea (Naumov, 2004)

During a particular 2003 expedition, an abnormally large number of icebergs (41) were recorded in the area. If this information were included in the probability analysis results mentioned above, the number of icebergs in each “N” year period (as well as the corresponding confidence limits) would be increased by approximately 300 percent.

Significant attention received from the studies performed by AARI researchers was attributed to the investigation of multiple parameters relating to iceberg trajectory. The mean velocity of icebergs in the Barents is 0.7 ft/s (0.2 m/s), and the maximum velocity is 3.9 ft/s (1.2 m/s). Model AARI studies indicated that the radius of tidal circulation of icebergs is on the order of 656 ft (200 m). A sample of actual iceberg trajectory recorded during three days, with hourly location marks, is presented in Figure D-5 (Naumov, 2004).

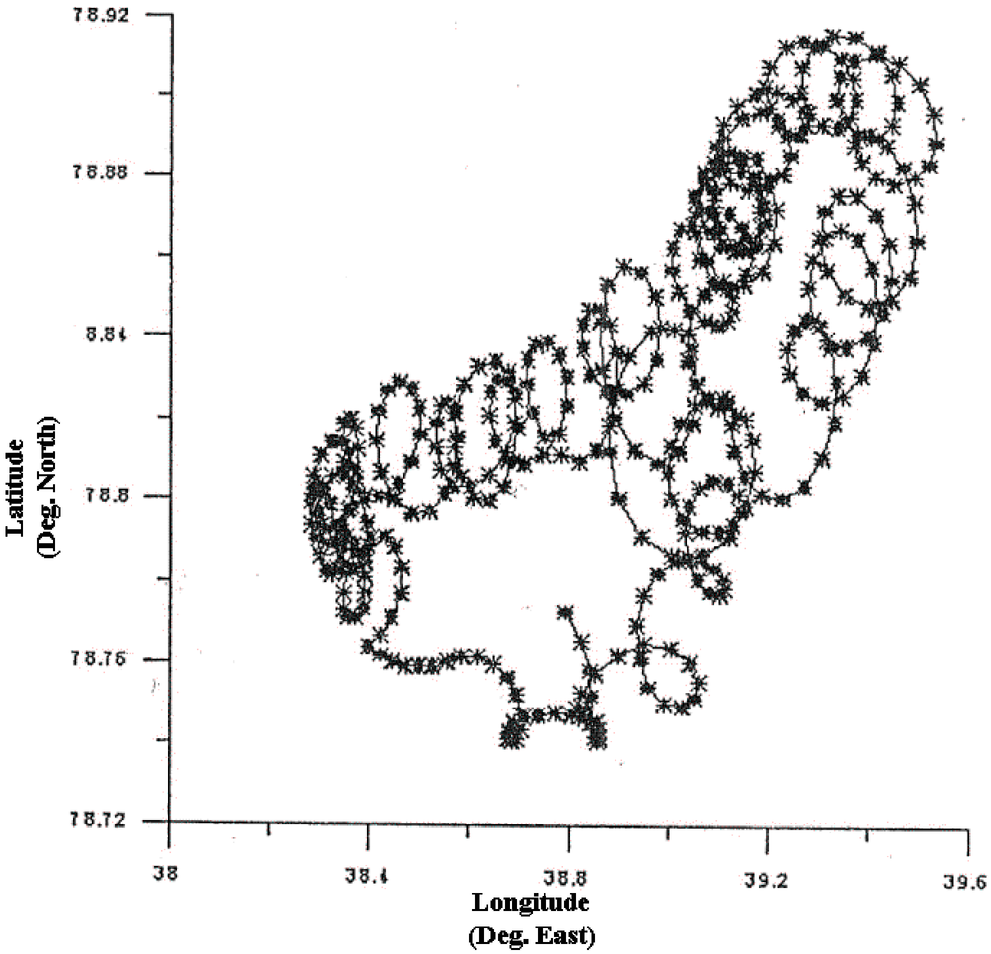

Figure D-5: Trajectory of Iceberg Drift with Hourly Location Points during 08-10.08.90 (Soviet-Norwegian Oceanographic Program, 1988-1992) (Naumov, 2004)

The evaluation of the probability of an iceberg colliding with a platform, in addition to the data mentioned above, required a number of basic assumptions. For instance, collision was assumed to occur when the distance between the center of the iceberg and the center of the platform was reduced to less than 1640 ft (500 m), and the probability of this event becomes higher than 0.95. Under these assumptions, the probability analysis of the available database (including the 2003 iceberg observations) indicated that collision of an iceberg with a platform at Shtokman is possible once in 35 years. It should be noted that Naumov (2004) stated that the abnormally large number of icebergs observed in the area in 2003 introduced a substantial uncertainty in the performed probability analysis and negatively affected its results.

The main data collected by AARI on the geometry of Barents icebergs is as follows:

- Maximum horizontal dimensions - 623 x 1411 ft (190 x 430 m)
- Maximum measured height - 68.2 ft (20.8 m)
- Maximum mass - 3.7 million tonnes
- Maximum draft (column iceberg) - 295 ft (90 m)
- Average mass - 870 thousand tonnes
- Average dimensions in plan - 236 x 394 ft (72 x 120 m).

D.4.3 Review of Existing Alternatives for Iceberg Management

Considering the substantial potential impact of iceberg intrusions on exploration work at Shtokman, Russian Arctic researchers performed a systematic review of iceberg management methods employed or being developed in the West, primarily in the US and Canada (Buzin, 2004a). Buzin (2004a) does not contain any indications of practical Russian experience in this field; however, at least two considerations specifically related to the conditions at Shtokman, are mentioned:

- At the time Buzin (2004a) was written (2003), the future platform for Shtokman was assumed to be a steel structure. The requirements for iceberg management at Shtokman may be particularly high.
- There exists a rather high probability (once in three years) that drifting ice (with relatively substantial coverage, and including two-year ice floes) may encroach on the Shtokman field. Presence of this ice will inevitably make application of current ice management technology very difficult, and there are no precedents of iceberg management in similar conditions in world practice.

D.4.4 Monitoring of Ice and Iceberg Conditions at Shtokman

The set of severe environmental / operational conditions described in the previous sections called for a reliable system of monitoring surveys at Shtokman, particularly with regard to icebergs. The extent of the iceberg problem was not always well understood. At the time when decisions to launch exploration work at Shtokman were initially made, icebergs were considered as a relatively rare event. However, findings from 2003 expeditions in the area "changed the problem from the hypothetical to practical" Buzin (2004b). The number of icebergs recorded in the area in 2003, according to Buzin (2004b), was 109. This number is more than twice as high as that mentioned in Naumov (2004), 41 icebergs (see Section D.4.2), but it is possible that the higher number (109) also accounts for fragments. After 2003, the design iceberg mass was significantly revised upwards (more than doubled), and more importantly, the probabilities associated with iceberg encroachment on the area and collision with the platform were substantially increased.

Initial Russian (AARI) proposals for iceberg-monitoring systems were built on practical experience and principals used at Hibernia or other projects that were proposed for similar conditions (Buzin, 2004b). For instance, the AARI proposed two safety zones for Shtokman. The outside ("strategic") zone includes the total area of the Barents Sea and encompasses sea areas adjacent to potential iceberg generation sources, such as Franz Joseph Land, the Northern Island of Novaya Zemlya archipelago, and Spitsbergen. The conditions within this outside zone are to be monitored at least once in 7 days, using equipment with resolution accuracy of at least 100-330 ft (30-100 m). The dimensions of the inside ("tactical") safety zone were not defined (as of 2004); however, it is assumed that it will be of rectangular shape and that the Shtokman field will occupy its southern portion. The northern limit of the inside zone shall be at approximately 76°N, see Figure D-2 and Figure D-3. Monitoring of the inside zone, in addition to satellite based equipment (with all-weather radar capabilities and resolution accuracy of at least 10-33 ft (3-10 m)), shall be performed using aerial surveys, as well as observations from drilling platforms and ships. Active monitoring programs shall be executed every one in three days.

The 985 ft (300 m) water depth in the area adds to the range of engineering challenges associated with stationary platform construction. However, when compared to the Newfoundland Grand Banks, Buzin (2004b) indicates that the risk of damage to seabed systems from iceberg gouging is lower at the Shtokman site.

D.4.5 Features and Properties of Ice Ridges in Eastern Barents Sea

During ice surveys conducted in the Eastern Barents in 2003, Russian scientists based on the research vessel "Mikhail Somov" performed a detailed investigation of ice ridges found at Shtokman. The prominent feature of this study was that the investigation covered large areas of two-year ice, which was never before observed in this area, or south of 75°N in general (two-year ice is more characteristic for the Northern Barents). According to Zubakin et al. (2004c), two-year ice was drifting into the Shtokman area throughout the 2002-2003 winter season from the North-east Kara Sea region. The investigation was conducted using an aerial survey, as well as from the ice surface (geodetic survey and mechanical drilling), and underwater (sonar, photography, and video).

During the drilling of ridges, ice fragment consolidation, ice texture, and crystal structure were evaluated. The cores extracted during drilling were used for temperature, salinity, density, and compression / flexural strength testing.

Multiple ridges formed from the interaction of one and two-year ice were composed primarily of one-year ice fragments with two-year inclusions. Ridges of this type were found at all ice observation stations in the Shtokman area. The following is basic information on the dimensions of 20 ridges surveyed:

- Length above water, average / maximum: 108 / 223 ft (33 / 68 m)
- Length underwater, average: 262 ft (80 m)
- Width above water, average / maximum: 46 / 125 ft (14 / 38 m)
- Width underwater, average / maximum: 66 / 131 ft (20 / 40 m).

Particularly interesting is the comparison of ridge dimensions presented in Figure D-6, (Zubakin et al., 2004c); data corresponding to the numbered lines within the figure come from the following sources:

1. AARI surveys in the Barents Sea during 1996-2001;
2. 2003 AARI survey (ridges with two-year ice inclusions); and,
3. National Research Council Canada (NRCC) report TR-1995-27 (one-year ice ridges, mostly Beaufort).

The triangular ridge models shown in Figure D-6 are generic in nature, but quite common in Arctic research. As can be observed from Figure D-6, the two-year ice ridges measured in Eastern Barents in 2003 are substantially smaller in size than a typical one-year ridge.

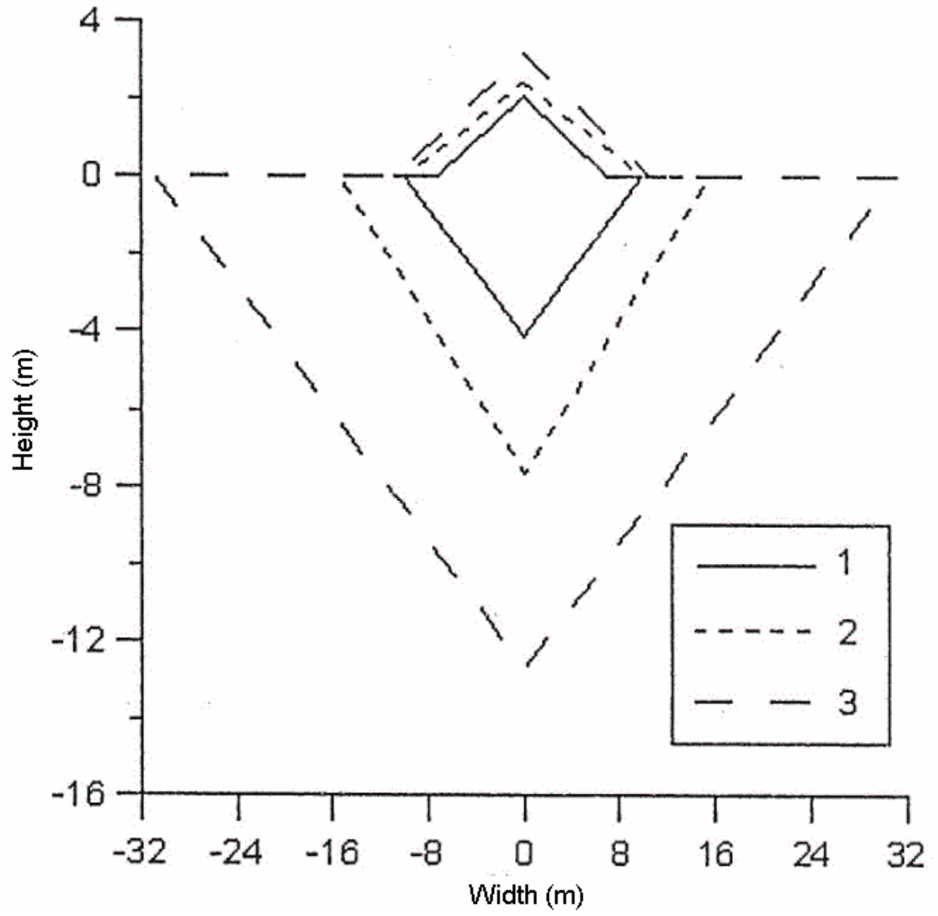

Figure D-6: Cross Section of Arctic Ridges with Averaged Horizontal and Vertical Dimensions (“0” along z-axis corresponds to sea level) (Zubakin et al., 2004c)

An interesting and significant phenomenon observed by AARI researchers is that while the sail height of two-year ice ridges is 50 percent smaller, their keel is just one-third that of one-year ridges; they explain the difference by the “genesis” of ridges, or, in other words, by the conditions at which the ridging occurs in these two cases. The net result of ridging with inclusions of two-year ice is the formation of structures, which are substantially more “leveled” or “smothered” than typical one-year ridges. This is most clearly illustrated by the differences in slope of ridge components (both the sail and keel of one-year ridges are 10-20 degrees steeper than those of two-year ridges measured by AARI in 2003).

The internal structure of ice in ridges investigated in 2003 had, on average, a degree of consolidation, which was 14 percent higher than that determined as a result of a five-year cycle of measurements performed by AARI in the South-east Barents. The calculated average consolidation coefficients for two-year ridges were 92 percent for sails and 94 percent for keels; these values are characteristic of monolithic ridges, which underwent a stage of melting and subsequent re-freezing.

Important conclusions from the series of tests on cores extracted in 2003 (from two-year ridges) were made with regard to ice strength. The mean value of ice compressive strength was 550 psi (3.8 MPa), which was found to be 2.14 times higher than that of the adjacent level ice. The mean value of flexural strength was 130 psi (0.9 MPa), which was 11 percent higher than of the adjacent level ice. AARI researchers consider these strength values unusually high for the Barents Sea, and explain them totally by the presence of the two-year ice in the tested material. The main trend indicating that the strength of ice in the ridges is higher than that in the level ice is not typical for the Barents. As explained in Zubakin et al. (2004c), the main reason for this finding is that similar testing, prior to 2003, was conducted only on the one-year ridges.

The most direct practical conclusion of the ridge survey performed during the 2003 expedition is that the possibility of intrusions of two-year ice, with more consolidated and higher strength ridges, apparently requires a step up in the design criteria for engineering structures being considered for Shtokman.

D.5 Ice Conditions in the Gulf of Finland

The Gulf of Finland is a sub-Arctic region, and strictly speaking, does not fit a description of the typical oil and gas Arctic shelf exploration area because it does not contain major hydrocarbon reserves. Yet, as a result of geopolitical changes associated with the disappearance of the Soviet Union, the Gulf of Finland has been left as the most convenient route for marine transportation of oil and gas from European Russia to Western Europe. The environment in the Gulf of Finland may be similar to sub-Arctic areas of the Canadian and American Arctic, and therefore present a certain interest for the current study.

Investigation of ice conditions in this area has a long history and multiple years of records exist. There are at least two reasons for the large amount of information available:

- The most significant scientific center of Arctic research in Russia (AARI) is in St. Petersburg, which is located at the East end of the Gulf
- The ice conditions in the area are so highly variable that only the detailed multiple year records may eventually yield a coherent general picture.

The common approach for evaluation of environmental conditions in the Gulf is to consider three general areas; the coastal zone, where the land fast ice quickly develops with the onset of winter; the near-shore strip, where the compression and ridging of ice floes prevails; and, the central portion of the Gulf, where conditions are favorable for unlimited ice drift (Drabkin and Lebedev, 2001).

The range of yearly variations is wide in all basic ice condition parameters: ice coverage, length of through-the-ice route from St. Petersburg to the relatively ice free open waters of the Baltic Sea, and level ice thickness. The variability of the last parameter is illustrated in Figure D-7 (Drabkin and Lebedev, 2001); as can be observed, maximum ice thickness in the Gulf ranges from 0.98-2.6 ft (30-80 cm), with a mean value of 1.8 ft (55 cm). The length of navigation in ice at the height of the sea ice season (March) varies from 85 nautical miles, in a mild winter, to 400 nautical miles, during a particularly cold year. The other characteristic feature is the “staged” development of ice conditions in the area, whereby the ice cover front advances westward from the eastern areas (Neva River mouth). While ice thickness in the Eastern part of the Gulf during cold winters may reach 2.6 ft (80 cm), it never exceeds 1.6 ft (50 cm) in the Western part. It may be expected that under these conditions, up to 30 percent of the Gulf area will be covered with ridges with 6.6-9.8 ft (200-300 cm) sails.

The tool proposed by the AARI for the forecasting ice conditions in the Gulf of Finland is a fully “interdependent” correlation matrix between seven parameters (Drabkin and Lebedev, 2001):

- Length of navigation in ice
- Total area of ice coverage in the Baltic
- Volume of ice in the Gulf of Finland
- Average air temperature during December-February period in St. Petersburg
- Average air temperature during December-February period in Helsinki
- Sum of negative temperature (degrees) X (days) in St. Petersburg
- Ice thickness in the Eastern part of the Gulf.

The relatively high values of coefficients of correlation received in the analysis (up to 0.80-0.90 in most cases) indicated that this approach indeed has a potential for reliable forecasting of ice conditions in the Gulf of Finland, and consequently for ensuring a higher safety for marine transportation of hydrocarbons in the area.

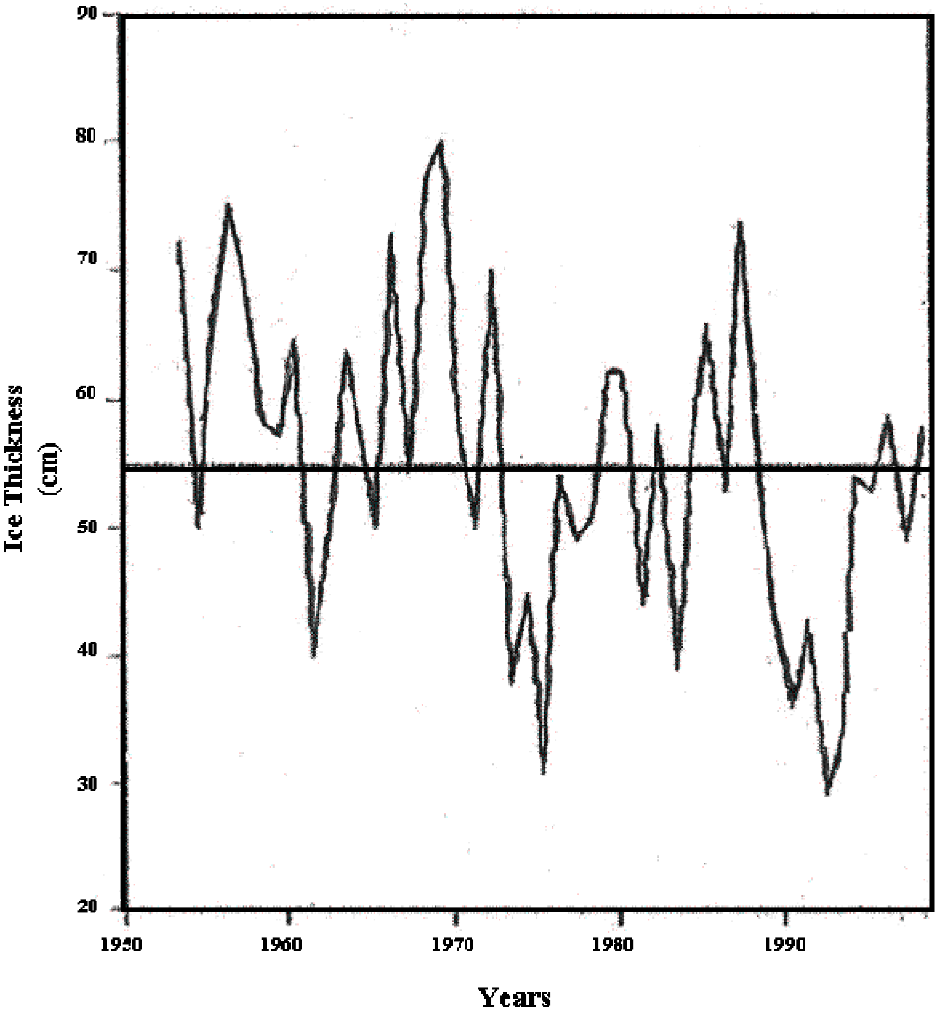

Figure D-7: Maximum Thickness of Ice in the Gulf of Finland (p. Ozerki) (Drabkin and Lebedev, 2001)